The Detection of Explosives using Robotic Crawlers

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***Abstract*-Chemical sensing of explosives may allow differentiation between mines and other mine-like objects, especially if close proximity to the targets can be achieved. Robotic crawlers are well suited to achieve the required proximity and have added advantages, including stability on the bottom and station-keeping. We have performed initial tests with an explosive sensor mounted on crawlers and two types of targets containing real explosives. In the tests, the robot successfully detected both targets at significant distances.**

For the initial test, the crawler approached the target from a direction upcurrent of the target so that any chemical signature emanating from the target would be transported away from the sensor. No sensor response was noted in this case. The robot was then repositioned by executing a number of turns placing the robot and sensor downcurrent from the target. Shortly after arriving in this position, intermittent sensor responses were observed. These responses were similar to what is observed in the laboratory. The response to the targets was rapid and reversible.

In order to gain insight into how most effectively to sample the area around mine-like objects, we are also simulating chemical orientation using spatial modeling and analysis tools.

I. INTRODUCTION

There are multiple ongoing efforts, both practical and theoretical, to apply robotic vehicles to mine detection. It is our belief that one of the most fruitful areas of application is in reacquire, identify and neutralize (RIN) type missions. In a RIN scenario in the surf zone a robotic crawler is expected to relocate a mine-like object that has been identified as such by another vehicle, make the final assignment with its onboard sensors, and possibly neutralize the object. A chemical sensor selective for explosives can aid in this task in several different ways. First, it can be used to help confirm an object is a real mine. Second, if sensitive enough, it can be used to lead the robot towards the target when the target is out of range of the other on-board sensors. Third, it can help localize a shallowly buried target.

Our current research has brought into sharp focus three distinct phases of a reacquisition search using a chemical sensor. The first phase (stereotypical search) is the initial transit to the expected coordinates of the mine-like object and the initiation of an optimal search pattern based on the original localization estimate. In this phase no new knowledge is available and the search must simply be based on the reported position of the mine-like target and its associated error circle or ellipse [1], if available. In this work we have assumed that this phase is designed to stop when a mine-like object is found or when the 95% error circle is searched completely. However, the actual ground track of the search pattern is based on the particular suite of on-board sensors since these determine the width of the swaths. Our main aim is to show that chemical sensors can be an important part of this suite of sensors and to show how the chemical sensor information can be used to aid reactive navigation towards the target.

This paper in part describes the results of a littoral field test conducted during February 2002 at the Coastal Systems Station with a newly developed in-water TNT sensor and a crawler robot. These field tests were performed to determine if the sensor could sense trace concentrations of TNT emanating from realistic targets placed in the water. During these tests it was shown that the sensor could sense the explosive emanating from a number of different targets at distances useful in the RIN scenario.

II. THE SENSOR

Real-time chemical sensing in the marine environment is in the early stages of development. In the particular case of explosive sensing, the dissolution flow emanating from a solid source can rapidly disperse in the environment, diluting the signature to levels that are difficult to detect. When steady currents are present this dispersion can be highly directional, making it necessary for the sensor to be positioned in the entrained density plume emanating from the source.

Suspended inorganic particulates, plankton and detritus further complicate chemical sensing by acting as sources and sinks of the chemicals of interest. Not only are there possible interferents that may interact with the sensor in a similar way as the analyte, but there are also more mundane issues such as clogging of the sample intake. Hence, a significant problem associated with detecting explosives in the marine environment is developing a sensor that is very sensitive and selective to explosives, yet rugged.

A TNT vapor sensor, which was originally developed under the DARPA Dog's Nose Program for the detection of landmines, was chosen for our initial tests. This sensor is

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based on a fluorescent polymer originally developed by T. Swager and his team at the Massachusetts Institute of Technology [2]. This vapor sensor was significantly modified in order to perform direct, real-time sensing of TNT in the aquatic environment without a need for sample preconcentration.

Preliminary work showed that when the polymer is exposed to water containing TNT, the intensity of emission from the polymer decreases dramatically in proportion to the quantity of TNT in the water. This initial test suggested that a simple flow through design would be suitable for a real-time crawler-based sensor.

For the initial tests, the sensor package consisted of two watertight boxes. The first box contained the sensing head and associated hardware to facilitate water passage through the sensing head. The sensing head contained a glass waveguide coated with a thin film of the fluorescent polymer. The coating on the glass rod was illuminated with light from a laser diode. The change in emission intensity of the polymer upon exposure to TNT was measured using a photomultiplier tube (PMT). The amount of light received by the PMT was then monitored using an onboard digital signal processor. The processed signal was transmitted to a shore station and monitored in real time by the sensor operator.

The second box contained a peristaltic pump and a servo actuator. Both the pump and servo were controlled electrically from the sensing head and were powered from the same power supply. The separation of the sensing head from the pump and servo provided electrical and mechanical isolation. The peristaltic pump was reversible and enabled operation at variable flow rates. The servo actuated a movable sample inlet tube that could be raised or lowered by remote control to enable precise positioning of the inlet in order to sample in three dimensions. A photograph of the sensor system, mounted on the robot crawler, is shown in Fig. 1.

III. THE INTEGRATION

The sensor and crawler were connected to a towed float that contained system batteries and communications hardware to transmit sensor and crawler data to and from the shore station. After initial system check-out, the TNT-sensing crawler was taken to a sandy beach area for mobility and integration trials. The system was then tested for basic operation underwater. After moving the TNT-sensing crawler into the water, the pump system was activated and the operation of the servo-controlled inlet was confirmed. These tests were successful, enabling sea trials of the system to begin. All targets in these trials were secured to a post located in four feet of water. Targets were suspended from the post by a rope so that the targets were approximately one foot from the sandy bottom. For initial tests, a target was

Fig. 1. Robotic crawler with sensor and sampling boxes mounted on top plate. Note the long sampling tube extending beyond the bumper.

constructed using the commercially available simulant TNT-NESTT (Non-hazardous Explosive for Security Training and Testing) produced by XM Materials. This target was placed inside a fabric bag and was affixed to the pole. Another set of trials were carried out with an explosive charge in the form of a ½ lb demolition block.

The same sampling procedure was used for all samples taken by the sensor. First the vehicle was stopped, then the peristaltic pump was turned on remotely after the video feed showed large particulates had settled. This normally took 10 or 20 seconds. This procedure minimized power consumption. The reversibility of the peristaltic pump allowed for backflushing of the sensor. In those instances where it was thought that a bolus of TNT had produced a persistent drop in the baseline, backflushing aided baseline recovery.

IV. TEST RESULTS

For the initial test, the crawler approached the target from the upcurrent direction so that any chemical signature emanating from the target would be transported away from the sensor. No sensor response was noted on this approach. By executing a number of turns, the robot was repositioned approximately one meter downcurrent from the target with the sensor inlet pointing towards the target. Shortly after arriving in this position, two sensor responses (seen in Fig. 2 near 230 seconds) were observed. These responses were consistent with that of TNT in water as demonstrated in the laboratory. The response to TNT was rapid and reversible and demonstrates the real-time nature of the sensor. Immediately after these responses were noted, the robot was positioned closer to the target, approaching to within 0.3 meters of the target from the downcurrent direction. The response at this position is indicated in Fig. 3.

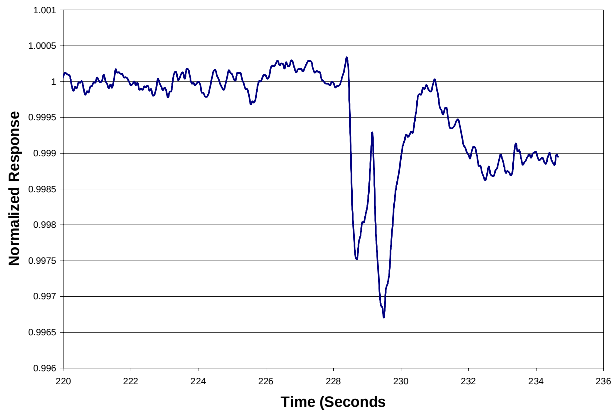

Fig. 2. Sensor response one meter downcurrent of target.

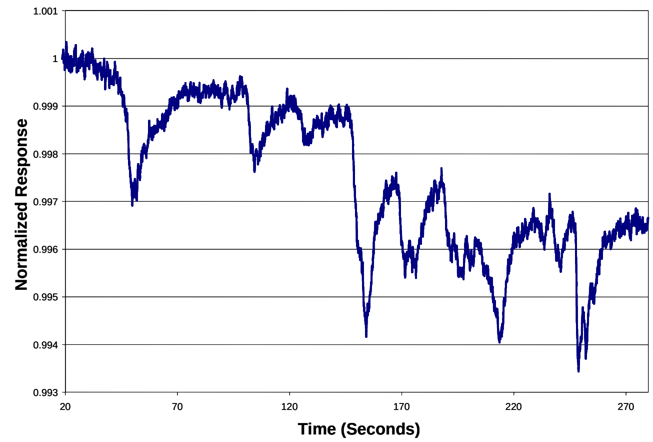

Fig. 3. Sensor response 0.3 meters downcurrent of target.

Once explosive is released from a target into water, it will likely be dispersed primarily through turbulent dispersion mechanisms. Turbulent dispersion produces domains of TNT separated by water containing little or no TNT. These higher concentration patches (containing TNT at a concentration higher than the plume cross-sectional average concentration) break down through the action of turbulence into smaller and smaller patches until complete mixing is achieved. Depending on environmental conditions, the TNT patches can persist at a significant distance from the source.

The sensor response noted in Fig. 3 is consistent with this type of dispersion mechanism. When a TNT patch was encountered by the sensor, several responses (sensor hits) were noted in quick succession. After the TNT patch clears the sensor, the emission of the polymer returns to near the initial baseline value as water with a much lower TNT concentration is drawn through the sensor. A comparison of Figs. 2 and 3 reveals that the frequency of sensor hits increases closer to the target. This is consistent with the assumption that the distance between detectable plume patches increases farther from the target. Also note that while the number of responses per unit time is greater near the target, the magnitude of the individual sensor hits is similar at both distances investigated.

In order to determine if the particular qualities of the NESTT material were responsible for the results observed the same test was carried out with a ½ lb demolition block of TNT. Qualitatively similar results were obtained away-from and near the target. This test also verified that the patches tend to fuse into a more-or-less continuous stream of hits when the intake is very near the target.

No responses consistent with the presence of TNT were observed unless the sensor was downcurrent from the target, suggesting that there were no interferents present in the water column during the test. Water samples were also collected at the site and were analyzed later. The water samples were then extracted into toluene and analyzed by Gas Chromatography/Electron Capture Detection (GC/ECD). The results confirmed the presence of TNT in the samples collected near the target. Laboratory analyses performed on the sensor after the field trial gave the calibration shown in Table 1. This calibration shows that most of the sensor hits translate to concentrations in the low parts per billion.

During these initial tests a couple of automated area search patterns were also tried. The sensor used for the tests registered significant deviations from baseline within a radius of 2.5 meters from the targets. However, the number of detection events at 2.5 meters was small and increased substantially at one meter from the target. This is why a preprogrammed upcurrent zig-zag search pattern did not offer a significant improvement over an upcurrent random search. It is clear from these initial attempts that autonomous vehicle operation will require more sophisticated (more intelligent) search patterns and a more sensitive sensor. The next generation sensor (Fig. 4) is many times more sensitive than the original prototype and promises to allow development of significantly improved autonomous behaviors.

Fig. 4. Next generation sensor with enhanced sensitivity is less than half the volume of the first generation.

V. MODELING EFFORTS

A. Overview

In parallel with the sensor tests we have proceeded with an effort to integrate the sensor with a crawler so that the vehicle can operate autonomously. In order to accomplish this, we are modeling several chemical orientation behaviors based on those found in aquatic organisms [3].

A significant amount of work has been published in the biological literature that describes the spatial distribution of encounter probabilities of chemical patch features such as peak concentration, concentration gradients at their leading edge, intermittency etc. [4]. Some of these stimulus features have shown spatial gradients that could be used to track and locate an odor source. These research efforts have demonstrated that at the measuring scale of animal sensors, purely chemoreceptive information can be extracted, from which the direction of distant odor sources can be estimated. Thus chemical orientation based on temporal analysis of odor patch features has become the favored hypothesis to explain orientation in a variety of organisms [3].

Bio-inspired reactive navigation using a chemical sensor to reacquire a target poses low risk (the behaviors have been tested by natural selection) and allows fastest implementation, since the behaviors that have been proposed in the literature are fairly simple and are not based on computationally intensive optimizations. In order to test these biologically-inspired behaviors, we have developed a simple stochastic spatial model that reproduces aspects of turbulence that we have found relevant to chemical orientation.

Our field data shows that concentration distributions can be best described as patchy and that detection of these patches is dependent on the sensitivity of the sensor. The patches themselves have a fractal character and are seen by the sensor as a sequence of closely spaced hits as is shown in Fig. 3. For this reason, direct use of concentration or its surrogate, sensor signal amplitude is difficult. The structure of the data suggests that a better metric is the frequency of sensor "hits". However, a distinction must be made between the closely spaced hits that signify a patch and the frequency of bursts associated with encountering multiple patches.

Thus, the field test results just summarized suggest that a multiscale fractal model may encompass the main features of the patch dispersion process, and allow the development and simulation of target homing behaviors in robotic vehicles. A simple fractal model based on these principles has been developed and implemented in a spatial simulation environment.

Concurrent with sensor detection events a measurement of the water current must also be made in order to calculate a new heading. In the model this is accomplished by sampling a spatial layer that contains the flow structure. The simulation environment also contains a simple mathematical response submodel of the underwater TNT sensor.

A set of behaviors can be programmed into the simulation environment and statistics can be collected on the ability of each behavior set to direct an agent towards the chemical source. The simulation environment is currently very simple, but is constantly being refined.

B. Search Routines

1) Stereotypical Search

Since crawler sensors are of more limited range than sensors mounted on other vehicles, and the probability is very high that an object is actually located in the vicinity of the coordinates given to the robot, the robot is programmed to perform one of three separate routines that will allow it to cover the highest probability area most effectively. These same routines have been incorporated into our simulation environment. The three patterns are 1) a random search, 2) a lawnmower pattern, and 3) an outward rectangular spiral. Several aspects make number 3 the preferred method among the ones listed. Method 3 can be made to have the original estimated coordinates of the object as the center of the search pattern, whereas the other two methods must include other constraints in order for the original estimate to be located at the center of the pattern. Secondly, methods 2 and 3 are the only ones that can be made to cover an area with probability 1 in the minimum amount of time. The area covered by the area-filling rectangular spiral can be expressed as,

$$AreaCovrd = W_s\left[\sum_{i=1}^{n}\left(L_0+\left((i-2)\cdot H(i-2)+(i+1)\cdot\left(1-H(i-n)\right)\right)W_s\right)-W_s\right] \tag{1.1}$$

where W_s is the width of the sensor swath, L_0 is the length of the first leg of the spiral, and H(x-y) is a modified Heaviside Step function,

$$H = \begin{cases} 0 & x < y \\ 1 & x >= y \end{cases} \qquad (1.2).$$

Each iteration *n* of this equation represents a rectangle.

There are several considerations to take into account when using such a search pattern. First, if some knowledge is available about the probability distribution of the location of the initial location estimate, this knowledge can be used to define the parameters of the rectangular spiral. In many instances standard surveying theory can be used to create either an error circle or an error ellipse where the object will be located within the circle or ellipse with 95% confidence. All that is required for an ellipse to be constructed is the assumption that the observations of object position are described by a multivariate normal distribution. The minimal rectangle that will contain this area can easily be calculated based on the major and minor axes of this ellipse which in turn are derived through standard approximations [5]. When only a few localization observations are available relative to the number of parameters in the localization model, the ellipse will be

large [1]. In this scenario chemical sensors can expedite the performance of the mission.

Fig. 5 shows an output map of a model that takes localization error into account. In this model scenario the crawler is given a location. This location is initially obtained by sampling a multivariate normal distribution several times. The robot is given the x and y sample average and the major and minor axes of the 95% error ellipse.

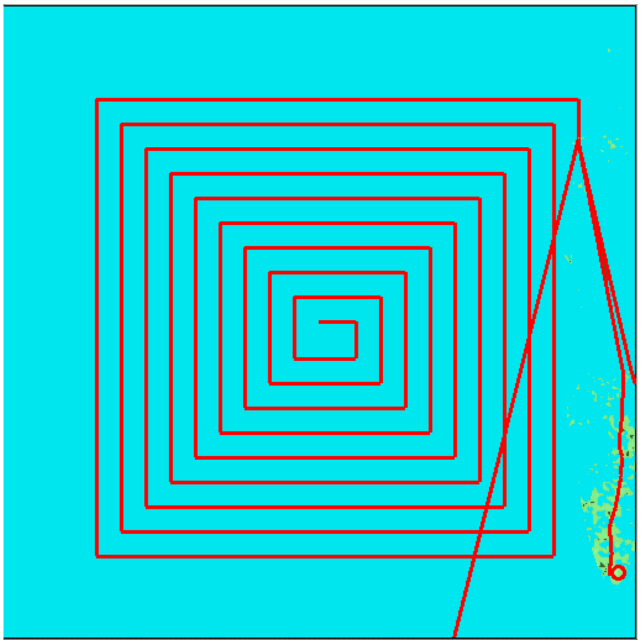

Fig. 5. Three search simulations run on the same plume structure but with different flow estimates.

2) Far-field search

The second stage of the reacquisition search (far-field chemical homing) encompasses the initial detection of the chemical signal, cessation of the stereotypical search pattern, and implementation of simple biomimetic behaviors. Fig. 5 shows a snapshot of the chemical patches (light green) emanating from a target (red circle) under a constant northward current. Even though the fractal model needs further refinement (to more realistically model edge behavior and patch fusion near the source), it has proved useful in fine-tuning the robot behaviors. Fig. 5 also shows three different runs with the same patch dynamics (shown as light green patches emanating from the source denoted by a red circle) but with different sampling of the simulated current flow. The robot's path (denoted in red) is the same outward spiral until the first patch is encountered. The three runs then deviate based on different estimates of the flow direction. The simulated field is 25x25 meters.

Following the studies of Moore and colleagues [4, 6-7] we have concentrated on three parameterizations of the strength of a simulated patch. These three are the amplitude of the largest sensor hit within a patch, the amplitude of the first sensor hit within a patch, and the within-patch hit frequency. The number of hits found in quick succession (weighted by their amplitude) can also be used to denote the strength of the patch and can then be used as the metric to modulate the robot's speed or distance of movement upstream. When it encounters a particular threshold of one or more of these parameters, the simulation breaks-off the stereotypical search and starts its chemical homing behavior.

The simulations show that since the patches spread in three dimensions, following the current upstream after the first patch is encountered decreases the distance to the target only up to a point. The salient qualitative conclusions obtained from the simulations are as follows.

- Far from the target, the patches are very sporadic, therefore, long excursions upstream between hits are preferred. These excursions should include directed-random or zig-zag reorientations with flow field sampling in order to ameliorate the effect of error in the initial direction estimate.
- As the chemical distribution becomes more continuous (i.e. the robot is closer to the target), edge following also becomes a sensible strategy.

3) Terminal Search

Our current model shows that our simple bio-mimetic behaviors often fixate on the boundary of the flow and can miss the target at low flow velocities when the target is relatively far from the nearest point on the boundary of the flow. This result is not unexpected, since it is known that in some organisms there is a clear distinction between the "far-field" search behaviors and the "near-field" ones.

Close to the target the concentration distribution is more continuous, and the parameterization based on patchiness is less effective. However, hits per time or weighted hits per time progressively become more effective estimators of the direction of maximum concentration (assumed to be the actual target). At this range, other close-range sensors can also be used to help detect the target with certainty.

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